The remote past and near future of electrocardiology: View-point of a biomedical engineer

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Ďaleká minulosť a blízka budúcnosť z hľadiska biomedicínskeho inžiniera

Abstract

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The major steps of advancement in electrocardiology over a period exceeding one century of its existence are briefly summarized, and some considerations concerning the most promising trends of its current and future progress are presented. *(Tab. 2, Fig. 2, Ref. 39.)*
***Ke*y words: electrocardiology, biomedical engineer.**

Abstrakt

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Práca stručne sumarizuje pokrok v elektrokardiografii, ku ktorému došlo počas jej viac ako storočnej existencie, a uvádza najsľubnejšie trendy jej vývoja v súčasnosti, ako aj v blízkej budúcnosti. *(Tab. 2, obr. 2, lit. 39.)*
Kľúčové slová: elektrokardiológia, biomedicínske inžinierstvo.

Our goal here is to characterize in brief the development of a branch of science which is commonly referred to as "electrocardiology". It should be mentioned that the term "electrocardiology" in contrast to that of "electrocardiography", denotes a scientific discipline, including its electrophysiological and biophysical aspects. G.L. Lempert was among the first to introduce the term "electrocardiology" in his book titled "Foundations of Electrocardiology" and published in Latvian (1961) and in Russian (1963) (1). These terms are still being used rather inconsistently, thus resulting in inappropriate titles of scientific meetings dealing with this field.

In this review, the major attention is focused on the history of evolution of fundamental principles of electrocardiological methods of diagnosis. The details of technological tools, particular procedures, and practical achievements of clinical electrocardiography are not described.

The high importance of electrophysiological and biophysical substance of electrocardiography, as well as of other instrumental diagnostic techniques, was emphasized by E.B. Babskii and V.V. Parin (2): "The task of the physiologist who is working out and creating a new research technique and testing a device is the physical-physiological analysis of the data which have been acquired with the use this technique or device. The necessity of such an analysis is dictated by the fact that it is not sufficient to find a new indicator describing the activity of organs and systems of the body, neither to develop a device for recording this indicator; one should determine the physical processes which cause the phenomenon investigated by the device, the physiological processes which correspond with this phenomenon, and reveal the physiological and purely medical significance of its determinination. It is only after having these questions clarified, application of this method becomes theoretically intelligent, only in this case the diagnostic and prognostic conclusions drawn from the results of applying this method in the clinic assume the sure ground.

A number of authors have presented various approaches in order to define the main chronological stages in the development of electrocardiology. In particular, in the survey by L.G. Horan (3) it is argued that the history of electrocardiography, including its "pre-

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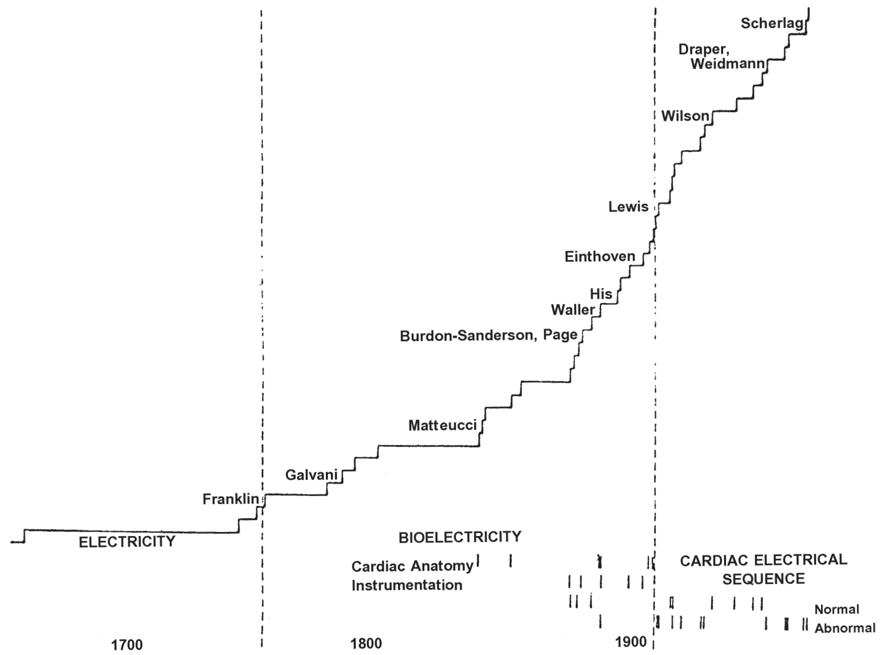

Fig. 1. Steps in the development of electrocardiography (based on the data of Comroe and Dripps) (3).

history", consists of three major periods (partly overlapping): "Era of Electricity" (prior to can 1750), "Era of Bioelectricity " (1750 to 1900), and "Era of Cardiac Electric Sequence" (after 1900), as shown in Fig. 1. The steps on the diagram correspond to particular advancements in the measurement techniques and diagnostic approaches that were the keys to subsequent clinical advancements. Here, the well known names of the founders of electrocardiology, such as Waller, Einthoven, Wilson, and others are indicated.

An interesting discussion on the development and mutual relation of electrophysiology and electrocardiography in the XIX century was presented by P. Rijlant (4).

A diagram to illustrate the periods of development of electrocardiology in the XX century was proposed by J.P. Boineau (5). This diagram is given in Fig. 2 with some additions made by the author of this paper. The history of electrocardiology is divided into "Ancient History" and "Modern Era". The latter began in 1957, following the New-York Academy of Science symposium. The proceedings of this meeting had a great impact, characterized as "Big Bang" in electrocardiology. In fact, the years prior to 1957 were the period of formation of electrocardiography, its introduction as a commonly accepted diagnostic technique, and the development of basic electrophysiological and biophysical concepts supporting this technique.

We review in brief some important achievements of this period, using information from the review papers (6,7,8), as presented in Table 1. Here experimental, theoretical, and clinical investigations alternate, however, no work are presented on the automation of electrocardiography and, naturally, neither on its computerization.

Beginning with middle of the nineteenth century, experimental measurements of electric potentials of animal hearts were carried out.

The first human electrocardiogram was recorded in 1887 by Waller, who pioneered in non-invasive leading of potentials from the chest surface and extremities, with the use of a mercury electrometer. Waller was the first to introduce the term "electrocardiogram" (nevertheless, some authors believe that this term was originally introduced by Einthoven). Waller already comprehended the electrocardiogram in its biophysical context, in particular, as a manifestation of electric potentials generated by the cardiac bio-

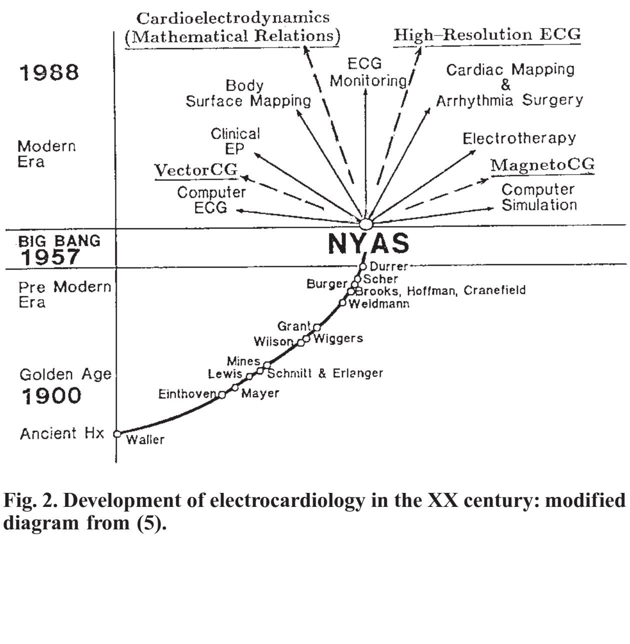

Fig. 2. Development of electrocardiology in the XX century: modified diagram from (5).

Tab. 1. Significant advancements of the "Ancient history" of electrocardiology (recording and interpretation of the electrocardiosignals).

Years of main publications – Authors – Achievements
1856 – A.KOELLIKER, H.MUELLER – Recording of potentials of the frog's heart by a galvanometer
1876 – E.J.MAREY – Recording of potentials of the frog's heart by the capillary electrometer on the photographic paper
1878, 1879 – T.W.ENGELMANN, J.BURDON SANDERSON, F.J.M.PAGE – Recording of potentials of the frog's and tortoise's hearts by a rheotome
1887 – A.D.WALLER – The first recording of the electrocardiogram (ECG) by an electrometer from extremities of man and dog; hypothesis of the dipole electrocardiogenerator; hypothetic map of distribution of the dipole potential on the body surface
1903 – 1913 – W.EINTHOVEN – Recording of the human heart potentials by a string galvanometer; nomenclature of the ECG parameters; standard leads I,II,III; general theoretical basis of electrocardiography
1909 –1925 – T.LEWIS, A.SAMOJLOFF – Principles of analysis of the cardiac rhythm by ECG; features of propagation of the excitation waves in the warm-blooded
1913 – G.R.MINES – Mechanisms of cardiac fibrillation
1914 –1920 – H.B.WILLIAMS, H.MANN – Constructing of vectorcardiogram (VCG)
1920 –1934 – F.N. WILSON – Concept of ventricular gradient, central terminal, chest leads
1936, 1937 – F.N. WILSON, F.D.JOHNSTON, F.SCHELLONG, W.HOLLMANN – Recording of VCG on the cathode ray oscilloscope
1936 –1953 – F.SCHELLONG, F.N. WILSON, G.E.BURCH, N.KIMURA, P.W.DUCHOSAL, R.SULZER, A.GRISHMAN, W.R.MILNOR, V.LAUFBERGER – Orthogonal vectorcardiographic lead systems
1942 – E.GOLDBERGER – Augmented limb leads
1942 –1951 – E.LEPESCHKIN – Generalization of theoretical and clinical-empirical know ledge on ECG in monographs
1946 – H.C.BURGER, J.B.VAN MILAAN – Theory of electrocardiographic leads, concept of the lead vector
1950 – L.A.WOODBURY – Recording of monophasic action potential of the animal's myocardium
1950 – F.N. WILSON, R.H.BAYLEY – Mathematical formulas for the potential of a dipole generator model in the spherical conductor
1951 – L.H.NAHUM – Body surface electrocardiographic mapping
1951 –1957 – R.P.GRANT, H.SCHAEFER – Concept of the electric axis of the heart
1952 – S.WEIDMANN – Electrophysiological characteristics of the myocardial cells
1953 – R.MCFEE, F.D.JOHNSTON – Theory of electrocardiographic leads, concept of the lead field
1954 – B.KAROLCZAK – Constructing of the isopotential maps on the human body surface
1954 –1961 – D.GABOR, C.V.NELSON, D.B.GESELOWITZ, D.A.BRODY – Multipole theory of electrocardiography
1954 – E.FRANK – Electrolytic-tank model of the body, a corrected orthogonal lead system
1955 –1961 – O.H.SCHMITT, E.SIMONSON, R.MCFEE, A.PARUNGAO, M.R.BARBER, E.J.FISCHMANN, R.A.HELM, C.V.NELSON, P.RIJLANT, H.KOWARZYK – Corrected orthogonal lead systems
1956 – I.T.AKULINICHEV – 5-plane lead system
1957 –1962 – A.M.SCHER – Recording of the intramural propagation of excitation in the dog's heart
1957– D.DURRER, R.T.VAN DAM – Recording of the propagation of excitation in the human and dog's heart wall

electric generator in the body functioning as a volume conductor. He suggested the hypothesis of the cardioelectric generator as a dipole configuration and illustrated this hypothesis by the well known Waller's diagram of the cardiac electric field.

However, Einthoven, whose major works were published in 1903, is commonly considered to be the true founder of clinical electrocardiography. He was the first to record the electrocardiogram by means of a string galvanometer, as well as to introduce the nomenclature of electrocardiogram deflections P, Q, R, S, T, to use the extremity leads I, II, III, to propose the "Einthoven triangle", to give the basic principles for interpretation of the standard electrocardiogram, and even to transmit the electrocardiogram through a telephone line. For the development in the field of electrocardiography he was awarded the Nobel Prize in 1924.

Table 1 presents also the achievements of many other well known scientists, which eventually resulted in a qualitative leap in the development of electrocardiology, indicated as the "Big Bang" in the Boineau's scheme (see Fig. 2). Here we shall not discuss in detail the details of the "Ancient History", and shift to the period called "Modern Era" of electrocardiology. Boineau recognized the following trends of development in electrocardiology, which have appeared to be prospective during the ensu-

Tab. 2. Sequence of conferences resulting in the modern Electrocardiological Congresses.

Numbers		Year	City, country	Organiser
COLLOQUIA ON VECTORCARDIOGRAPHY				
0		1959	Wroclaw, Poland	Kowarzyk
1		1960	Wroclaw, Poland	Kowarzyk
2		1961	Stary Smokovec, Czechoslovakia	Ruttkay-Nedecky
3		1962	Zakopane, Poland	Kowarzyk
4		1963	Liblice, Czechoslovakia	Laufberger
5		1964	Prague, Czechoslovakia	Kowarzyk, Laufberger, Ruttkay -Nedecky
6		1965	Leipzig, Germany	Schubert
7		1966	Smolenice, Czechoslovakia	Ruttkay -Nedecky
8		1967	Wien, Austria	Wenger
9		1968	Moscow, USSR	Amirov
10		1969	Jablonna, Poland	Kowarzyk
11		1970	New York, USA	Hoffman
12		1971	Bruxelles, Belgium	Rijlant
13		1972	Dresden, Germany	Schubert
14		1973	Yerevan, USSR	Dolabjian
INTERNATIONAL CONGRESSES ON ELECTROCARDIOLOGY				
15	I	1974	Wiesbaden, Germany	Abel
16	II	1975	Varna, Bulgaria	Pavlov
17	III	1976	Bruxelles, Belgium	Kornreich
18	IV	1977	Balatonfured, Hungary	Antaloczy
19	V	1978	Glasgow, United Kingdom	Macfarlane
20	VI	1979	Yalta, USSR	Amirov
21	VII	1980	Lisbon, Portugal	de Padua
22	VIII	1981	Budapest, Hungary	Antaloczy
23	IX	1982	Tokyo, Japan	Ueda
24	X	1983	Bratislava, Czechoslovakia	Ruttkay -Nedecky
25	XI	1984	Caen, France	d'Alche
26	XII	1985	Minsk, USSR	Sidorenko, Amirov
27	XIII	1986	Washington, USA	Rios
28	XIV	1987	Berlin, Germany	Schubert
29	XV	1988	Wiesbaden, Germany	Abel
30	XVI	1989	Budapest, Hungary	Antaloczy
31	XVII	1990	Florence, Italy	Taccardi
32	XVIII	1991	Warsaw, Poland	Jagielski
33	XIX	1992	Lisbon, Portugal	de Padua
34	XX	1993	Kananaskis, Canada	Rautaharju
35	XXI	1994	Tokyo, Japan	Harumi
36	XXII	1995	Nijmegen, Netherlands	Van Oosterom
37	XXIII	1996	Cleveland, O., USA	Liebman
38	XXIV	1997	Bratislava, Slovakia	Bacharova
39	XXV	1998	Budapest, Hungary	Preda
40	XXVI	1999	Syktyvkar, Russia	Roshchevsky

ing years: computer electrocardiography, clinical electrophysiology of the heart, body surface mapping, electrocardiographic monitoring, cardiac mapping for surgical treatment of arrhythmia, electrotherapy, computer simulation.

It should be noted that the scheme includes non-invasive as well as invasive methods, along with techniques of acting upon the heart by an external electric field. The directions of advance in electrocardiology such as conceptually new vectorcardiographic methods, cardioelectrodynamics (mathematical relations and modeling), high-resolution electrocardiography, and magnetocardiography (the dashed arrows in Fig. 2) are added to the initial scheme by the author of this article.

The rapid progress in theoretical and experimental investigations devoted to electrocardiological problems, as well as their wider application in diagnostic practice, was followed by an increase in the number of corresponding publications, scientific and scientific-organizational conferences, enhancing the rise in significance of electrocardiology as a scientific discipline and stimulating the achievement of its higher level of quality and diagnostic efficiency.

Among the periodicals dealing with electrocardiological themes, especially remarkable is the “Journal of Electrocardiology” founded in 1968 by Z.A. Zao and E. Lepeschkin and presently edited by R.H. Startt-Selvester.

We should note that the following books have played a great part in generalizing the theoretical basis of electrocardiography in the context of electrodynamics, and laid the groundwork for the present and prospective methods of the measurement and interpretation of electrocardiographic data: the classical book “Bioelectric Phenomena” by R. Plonsey (1969) (9) and the collective monograph “The Theoretical Basis of Electrocardiology” edited by C.V. Nelson and D.B. Geselowitz (1976) (10). Problems of the same area were discussed later, in particular, in the book “Electric Generator of the Heart” by L.I. Titomir (1980, in Russian) (11), “Cardiac Electric Field” by I. Ruttkay-Nedecky (1983, in Slovak) (12), “Bioelectricity: A Quantitative Approach” by R. Plonsey and R.C. Barr (1988) (13), “Bioelectric and Biomagnetic Fields: Theory and Applications in Electrocardiology” by L.I. Titomir and P. Kneppo (1994) (14); “Bioelectromagnetism: Principles and Applications of Bioelectric and Biomagnetic Fields” by J. Malmivuo and R. Plonsey (1995) (15); and “Mathematical Modeling of the Cardiac Bioelectric Generator” by L.I. Titomir and P. Kneppo (1999, in Russian) (16).

The unique three-volume monograph “Comprehensive Electrocardiology: Theory and Practice in Health and Disease” edited by P.W. Macfarlane and T.D.V. Lawrie (1989) (17) can serve as an especially rich source of knowledge in the area of electrocardiology. This book is encyclopedic by its nature, it is written by the most prominent experts at corresponding problems of electrocardiology, and contains concentrated information on electrocardiology available by that time. Presently, the exchange of information in this area is facilitated by the new WEB site “ECGNet Forum” being edited by L. Bacharova.

The rapid development of electrocardiology has enhanced the organisation of scientific meetings and conferences, formation of structures providing exchange of information, and international cooperation of specialists. Presently, the traditional conferences exclusively devoted to electrocardiological subjects are the International Congresses on Electrocardiology, which are held annually in various countries (Table 2). The history of these congresses is presented in brief in (18).

In 1959, the Colloquia on Vectorcardiography initially organized by H. and Z. Kowarzyk began to take place. Later on, P. Rijlant and other scientists actively participated in organization and implementation of these meetings. Soon afterwards, it became clear that the subject of these Colloquia is not limited by the scope of vectorcardiography, and for some time their title was changed to “Symposia on Electrocardiology”. Finally, it was decided to name them “International Congresses on Electrocardiology”. The First International Congress on Electrocardiology was held in Wiesbaden, Germany, in 1974. Other international conferences dedicated to particular aspects of electrocardiology are also held, for example, the conferences on computerized electrocardiology, bioelectromagnetism, etc.; however, the International Congress on Electrocardiology is considered to be the major annual international meeting dealing with this field. The published proceedings of these congresses accumulate the latest and most pertinent information on the advancement in this field.

In 1983, the International Council on Electrocardiology was formed to coordinate organization of congresses and to support any other activities facilitating the development of electrocardiology. In 1993, the International Society of Electrocardiology was founded, while the aforementioned council became “the Council of International Society of Electrocardiology”. This Council includes experts from about 10 countries, actively solving various problems of electrocardiology.

Let us once more turn to Fig. 2 and consider the main directions and stages of development of electrocardiology during the “Modern Era”, which, according to the diagram, began in the early sixties. All indicated tendencies have in fact proved to be efficient, and at present they continue to progress even more actively. Some of them have gained wide acceptance in practical diagnostics, other still remain in the stage of research and improvement; and some, because of their expensiveness and complexity, are accessible only for few large-scale medical institutions.

We will draw the attention to one of the trends, which is indicated in the diagram as “Computer ECG”. At the time when this diagram was presented, the computer electrocardiography meant an automatized diagnostic technique performed by use of a computer, based on implemented algorithms of formalized logic of cardiologists (i.e. standard electrocardiographic parameters, namely, wave amplitudes and intervals of scalar electrocardiographic curves, and so on), or on the rules of statistical classification. About 20 years ago, a great number of such diagnostic computer programs had already existed.

In the last decades, the computerized data processing and elements of information technologies became in fact an integral part of all advanced techniques of diagnostic interpretation of electrocardiographic signals. Hence, the period called “Modern Era” turned into the “Era of Computerized Electrocardiography”. The history of computerized electrocardiographic systems, although relatively short, can be subdivided into characteristic stages. These stages are usually referred to as generations of computerized electrocardiographic systems, rather than epochs or eras.

Let us first consider in general the following most fundamental ways to solve the problem of improving the accuracy and practical efficiency of electrocardiographic diagnosis:

1. Increasing the informativity of the initial (measured) data, in particular,
— optimally positioning the lead electrodes on the body surface;
— synchronously recording the lead signals;
— increasing the number the leads;
— widening the frequency band of signals being recorded;
— increasing the duration of signal measurement;
— measuring the magnetic field of the heart along with its electric field;
— widening the scope of anthropometric measurements.

These approaches have obviously been used in the development of such methods as vectorcardiography, electrocardiographic mapping, magnetocardiography, electrocardiographic monitoring, high-resolution electrocardiography, and so on.

2. Improving the quality of mathematical processing of data, in particular,
— increasing the resolution of initial parametrization (analog-digital conversion) of signals;
— developing algorithms for statistical classification of data with the use of various quantitative parameters (empirical approach);

— formulating the biophysically and electrophysiologically substantiated parameters, as well as mathematical models of bioelectric processes in the heart;
— using intelligible-pictorial representations of the cardiac electric field and electric generator which can be estimated by visual (heuristic) methods with sufficient accuracy.

3. Increasing the general amount of electrocardiographic information and intensity of its exchange on the basis of computerized data bases and telecommunications, in particular,
— forming the extensive electrocardiographic and relevant non-electrocardiographic data bases;
— active exchange of electrocardiographic information and diagnostic techniques between specialists;
— efficient computer-assisted training of experts in electrocardiographic diagnosis;
— providing easy accessibility of electrocardiographic diagnostic procedures for non-specialists in electrocardiography, up to a ”diagnostic self-service” of patients.

4. Ensuring the most harmless, comfortable, technically simple, and sufficiently cheap electrocardiographic measurement procedures, in particular,
— using the minimum possible number of leads;
— positioning the electrodes according to a convenient symmetric set-up;
— using a wireless design of measurement equipment.

It is obvious that a part of the just listed trends of development of computerized electrocardiographic (ECG) systems are in mutual contradiction. Nevertheless, their combination can result in a significant improvement of ECG techniques, and facilitate the solution of many particular diagnostic tasks.

Hence the use of synchronous measurements and representation of cardiac electric activity in the form of vector loops provided the basis for vectorcardiography, which had been introduced even in the “Pre Modern Era” and later refined by many researchers. The diagnostic efficiency of this method has been verified by numerous experimental-clinical investigations, and thus justified for wider practical application.

The use of synchronous multiple leads and mapping of cardiac electric activity is characteristic for the “topographic” trend in electrocardiology (19, 20). The most commonly used version of this method resides in mapping of the measured potentials which are straightforwardly superimposed on the measurement surface, that is on the surface of the chest (body surface potential mapping). There are countries where this diagnostic technique is widely used in many medical institutions (21). Many ECG mapping experts consider this method to be extremely promising. Particularly, Liebman entitled an article devoted to this method “The Electrocardiogram of the Future” (22). However, there in he emphasized the difficulties of its practical implementation, such as complexity of measurement procedures and considerable problems with data interpretation.

Further advancement in electrocardiology is directly related to quantitative representation of data on the basis of an accepted mathematical model of the cardiac bioelectric generator in biophysical and electrophysiological terms, with relations to the anatomical structure of the heart. Such a representation significantly facilitates the heuristic visual analysis of data and, in combination with empirical quantitative approaches, provides a steep rise in efficiency of ECG diagnosis. In this way, however, fundamental difficulties emerge. There is, first of all, the physical ambiguity of the cardiac bioelectric generator determined by the potentials measured on the body surface. The so-called inverse electrodynamical problem should be solved, while its solution can be obtained on the basis of efficient mathematical models of the cardiac bioelectric generator, which are referred to as equivalent generators. These models must ensure a unique solution of the inverse problem and at the same time represent the electrogenic processes of cardiac excitation in form of electrophysiologically meaningful characteristics with a sufficiently clear relation to anatomical parts of the heart. Here, the use of latest achievements in biophysics and electrophysiology of the heart in association with computerized data processing is especially important (23).

There are several attempts which are known to categorize the computerized ECG systems into typical stages of development, or generations, based on some particular properties or factors. For instance, Furukawa and Tanaka (24) recognize three generations of techniques for solution of the inverse electrodynamical problem in electrocardiology: 1) solutions in the form of point (discrete) equivalent generators; 2) solutions in terms of distributions of potentials on the heart’s surface or near it; 3) solutions in the form of equivalent generators distributed over the volume or surfaces of the cardiac structures (such solutions most closely approximate the actual cardioelectric generator).

In other approaches, the stages of development (possibly, also called “generations”) are considered for the computerized ECG system as a whole, whereas such a system is meant to be a set of automatized means including the measuring and computing equipment together with appropriate mathematics and software (25). Following the ideas of Pipberger and his co-authors (26), the sequence of conceptual improvements of such systems may be represented in a generalized form as several periods, or levels. Any transition to a higher level produces a new quality of systems, which is designated, in part tentatively, as a new generation of systems.

If the major stages of data processing are supposed to be composed of data acquisition, mathematical description, automatic classification, and graphic, or visual representation, then the transition to each next level is accomplished in accordance with a rather rapid, almost stepwise qualitative improvement in one of the data processing stages. These conceptual transitions are as follows: from the physician’s formalized logic to statistical classification rules; from the standard 12 leads to multiple synchronized leads; from the curves of the temporal variation of electric potential to pictorial visualization of physiologically meaningfull parameters distributed over appropriate anatomical volumes or surfaces. Thus, here the concept of the fourth generation system is strongly related to advancment in the field of automation of descriptive, or intelligible-pictorial data visualisation.

It should be ascertained that the emergence of new generations of computerized ECG systems closely corresponds with progress in computer and information technologies, rapid development of new methods of mathematical description, information analysis, and graphic imaging of data, in particular, increasingly wider use of techniques based on artificial neural networks, expert systems, clinical workstations, and so on (27—29, etc.).

In recent years, a dramatic increase in the power of computerized information and communication networks also brings nearer solution of problems such as creating multi-purpose ECG-data banks of practically unlimited capacity (containing, along with electrocardiographic records, any appropriate data on observed patients); interactive on-line data exchange between the patient and physician; implementation of diagnostic procedures for the purposes of personal diagnosis, dynamical observation of the patient's state, self-observation of the patient, integration of accumulated experience, supplementation of data bases, organization of consultations and continuous training in ECG diagnostics, and so on (30, 31, etc).

In the context of rapid improvement of automation of ECG diagnostics and widespread use of the so-called interpretative electrocardiographs and systems transmitting the electrocardiograms through telecommunication lines, an urgent question arises as to the relation between the quality of electrocardiogram interpretations by expert-cardiologists and by the diagnostical computer program. Here we are dealing with estimation of possible limitations in automation of ECG diagnostics and prospects for total replacement of cardiologists by interpretative electrocardiographs. Leading experts in this field are inclined to conclude that the requirement of active participation of cardiologists in taking ultimate diagnostic decisions remains quite justified (32—35, etc.). It should be noted that even in the absence of specialized means facilitating the visual data analysis and user-system interaction, the visual estimation of the initial standard ECG curves by cardiologists often improves the accuracy of their ultimate diagnostic conclusions, as compared with those made by the computer. At the same time, disclosure of the computer diagnosis frequently improves the accuracy of the cardiologist's diagnosis conventionally obtained by his own electrocardiogram analysis.

The advanced computerized ECG system, which presents data in pictorial form with electrophysiological and anatomical substantiation, not only carries out automatically most of the "external" processing of the data, but also promotes the "internal" processing accomplished by intuitive models and decision-making mechanisms of cardiologists, who use their professional skill and particular experience. The importance of such an "internal" processing of information participating in diagnostic procedures was emphasized in an early paper by Barnard (36), and later by other authors.

The above versions of the subdivision of computerized ECG system history into levels, or generations, should not be understood on a too strict basis. Here, only the most significant periods of development and the most important properties of systems are referred to. Particular systems may embody various properties typical for different levels. Usually, systems of any generation absorb all efficient methods inherited from preceeding generations, and implement their abilities under new circumstances with greater success. This is illustrated by the following examples.

As noted above, the improvement of electrocardiological techniques is carried out not only in increasing their accuracy, but also in providing maximum total efficiency of the diagnostic procedure, including its acceptability for wider use and economic feasibility. Thus, it is important to use the achievements in data acquisition and processing typical for systems of new generations, however without making the measurement procedure too complicated.

One such approach has been implemented in the method of dipole electrocardiotopography (DECARTO) (37). Here, only three synchronous signals of a corrected orthogonal lead system (belonging to the systems of previous generations) are used. However, owing to a sufficiently substantiated (while appropriately simplified) model of the cardioelectric generator, a pictorial mapping of main electrophysiological states of the heart with graphically superimposing electrophysiological characteristics onto the anatomical scheme of the heart is accomplished.

A system of kinematized intelligible-pictorial imaging of electrocardiograms, using a modified standard lead system and mathematical models of cardiac excitation, with implication of appropriate non-electrocardiological information, is strongly substantiated in (38,39).

Nowadays, theoretical and experimental investigations directed toward the elaboration and practical application of computerized ECG systems of new generations are actively carried out by many scientific groups and institutions. The new ideas used as the basis for this development foresee construction of an individualized computer model of the heart in the form of a virtual biological object with corresponding anatomical and physiological characteristics (including electrophysiological) involved by a system of information exchange by extensive interactive internal and external communications. It is believed that the trends of computerized electrocardiology will bring this method to even a higher level of efficiency, so that it may be referred to as computerized non-invasive electrophysiological imaging, or even electrophysiological introscopy of the heart.*

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